

Fiber Cavity Ring-Down Using an Optical Time-Domain Reflectometer

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Abstract: This work presented a demonstration of the potential for a fiber based cavity ring-down (CRD) using an optical time-domain reflectometer (OTDR). The OTDR was used to send the impulses down into about 20km of a standard single optical fiber, at the end of which the fiber cavity ring-down was placed. The OTDR measured no appreciable losses, so other CRDs multiplexed could be spliced in parallel along the same optical fiber. To demonstrate the behavior and sensitivity of the proposed configuration, a displacement sensor based on a fiber taper with a diameter of 50 μm was placed inside the fiber loop, and the induced losses were measured on the CRD signal — a sensitivity of $11.8 \pm 0.5 \mu\text{s/mm}$ was achieved. The dynamic range of the sensing head used in this configuration was about 2 mm. Finally, this work was also compared with different works published in the literature.

Keywords: Optical fiber sensors, cavity ring-down, OTDR

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1. Introduction

The cavity ring-down (CRD) spectroscopy is a widely used technology for chemical and molecular analysis in real time [1]. The evolution of this technique leads to the development of diverse configurations based on the same underlying principle, i.e., a resonant optical cavity with high reflectivity mirrors [2, 3].

The recent development of a fiber optic based CRD, which uses a fiber loop as the resonant cavity, has been gaining popularity in the community, for presenting a potential alternative to the usual CRD

[4]. In this manner, the conceptual study of the CRD technique became a focus of attention in the area of optical spectroscopy, for the last decade. Only recently, this technique has been applied to the measurement of physical parameters, such as deformation [5, 6], pressure [7], and temperature [8].

Nowadays, biochemical sensing has been the main topic of this area of research. Several schemes based on the CRD technique in the optical fiber have been implemented, such as for gas detection [9], detection of liquid phase [10] and unicellular organisms [11], detection of xylene and cyclohexane

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[12], and recently, the measurement of rhodamine 6G in the aqueous solution [13]. The CRD technique has also been applied for refractive index sensing [14–18].

The flexibility of this technique has allowed using as the resonant cavity in the fiber loop a variety of sensing devices such as long period gratings, fiber Bragg gratings, fiber microchannels, and photonic crystal fibers. The combination of sensing fiber devices with the CRD technique has shown the possibility of obtaining the high sensitivity and resolution, providing the means for the development of a new generation of optical fiber sensors with strong applications to biochemical sensing and sensors in biological systems.

In this paper, we present the potential for a CRD-based configuration by using an optical time domain reflectometer (OTDR), instead of the usual laser and modulator setup, to send the impulses into a fiber-based cavity ring placed after a long extension of the fiber [19]. A fiber taper with a diameter of 50 μm was placed inside the fiber loop with about 800m and used as a displacement sensor in order to induce losses on the CRD signal. The optimization of the pulse signal provided by the OTDR was also performed.

2. Theory

The fundamental principle of fiber cavity ring-down is simple. An optical pulse is made to travel in a fiber loop, which usually has two couplers, one for the source and the other for measuring the intensity of the pulse, thus forming the analogue of the mirrors in a traditional CRD. Due to the losses in the couplers and the fiber intrinsic attenuation, the pulse will slowly decay as it travels around the loop. If the losses are not too high, the pulse will still take several turns through the loop, and one would measure it at a given position, as it passes. One then observes a series of pulses equally spaced in time (by an amount $t = nL/c$ where L is the length of the cavity and n the

effective refractive index of the fiber) and with increasingly smaller intensities.

In the fiber loop, one may then place an intensity sensor T_s which measures some physical parameters. For each round trip through the loop, the pulse gets attenuated by the same factor, which depends on the fiber attenuation, the couplers insertion losses T_c , and the sensor transmission T_s . After one turn, the intensity of the pulse drops by the factor [10]

$$\frac{I_1}{I_0} = T_s T_c^2 \exp(-\alpha L). \quad (1)$$

After k turns (or the time t_k),

$$\frac{I_k}{I_0} = \left(\frac{I_1}{I_0} \right)^k = e^{(t_k/\Delta t) \ln(I_1/I_0)} = e^{-t_k/\tau}. \quad (2)$$

The exponential decay of the pulse can be characterized by its time constant τ [10]:

$$\tau = \frac{nL}{c[\alpha L - \ln(T_s T_c^2)]}. \quad (3)$$

The sensing principle lies on the dependence of the decay time with the sensor transmission T_s . Since the pulse travels several times through the intensity sensor, high sensitivities can be attained with this technique.

Before calibrating the sensor, the behavior of the output signal is studied as a function of the OTDR pulse width. Different pulse width values are applied in the range of 0.5 μs – 20 μs . Figure 1 shows the

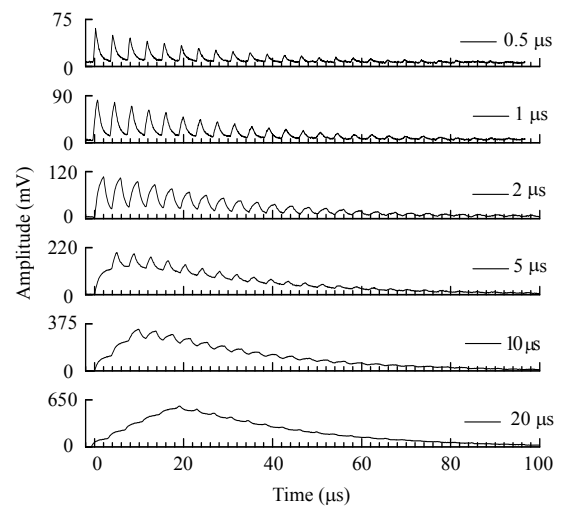


Fig. 1 Cavity ring-down trace for different OTDR pulse widths.

waveform output signal for each pulse width applied to the CRD. Only two waveforms can be used in the proposed configuration, namely, $0.5\ \mu\text{s}$ and $1\ \mu\text{s}$, since the remaining waveforms present signal saturation. However, in this work, the OTDR was used to send $1\text{-}\mu\text{s}$ impulses into the CRD because the signal amplitude was higher than the previous one ($0.5\ \mu\text{s}$).

3. Experimental results

The experimental setup of the proposed CRD system is presented in Fig. 2.

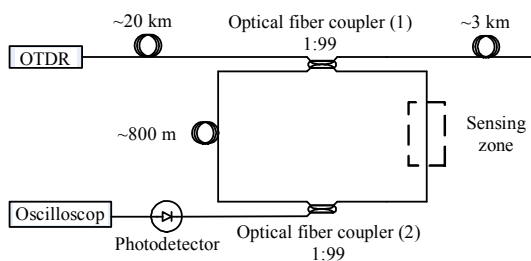


Fig. 2 Cavity ring-down setup (the signal is introduced by the OTDR and monitored by means of a photodetector and an oscilloscope, and the depicted sensing zone is where a sensing head may be added).

A commercial OTDR, Yokogawa AQ7270, was used to send $1\text{-}\mu\text{s}$ impulses down into an optical fiber (SMF 28), which, after an extension of around 20 km, was coupled to a fiber loop through a 1:99 directional coupler (1). The 800-m fiber loop formed the cavity where the pulse ringed around and was coupled out by means of a second 1:99 optical coupler (2); a 3-km fiber was placed in the free output coupler arm in order to reduce the Fresnel reflection that might originate some instability in the input signal. The photodetector detected the amplitude decay of the output pulses, and the measured signal was observed in an oscilloscope, which is depicted in Fig. 3. An exponential fit was performed, as shown in Fig. 4, and a ring-down time of $32\ \mu\text{s}$ was attained. This value depended strongly on the losses originated by the length of the loop, splices, and insertion losses of the fiber couplers. The decay time might also be changed appreciably upon introduced losses, for example, with the bending of the fiber. To explore such behavior in the

CRD setup, a simple intensity sensor was introduced in the loop between the two optical couplers, as shown by the sensing zone marked in Fig. 2. The sensing head was based on a tapered singlemode fiber with the $50\text{-}\mu\text{m}$ diameter, placed on a translation stage. The typical behavior of this sensor is used for several applications, namely, for the measurement of physical parameters. In this case, the taper was used as a displacement sensor, and when forcing the taper to bend, measurable losses were induced in the CRD signal.

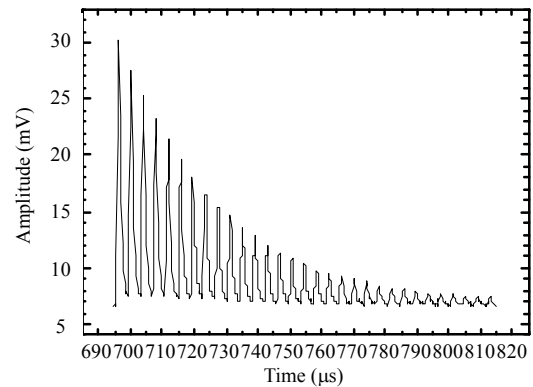


Fig. 3 Cavity ring-down trace for the 800-m fiber loop.

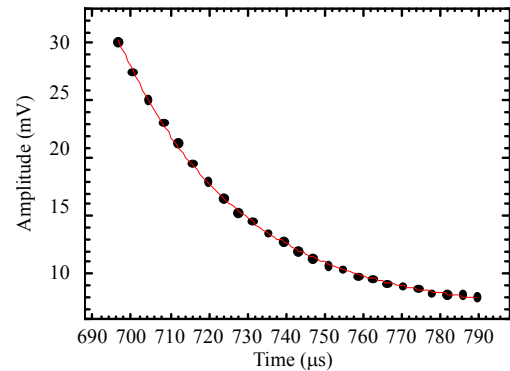


Fig. 4 Exponential fit of the peak amplitudes obtained from Fig. 3 and from which the decay time was calculated.

This analysis was reproduced for several displacement values. The different associated losses led to different decay time, as observed in Fig. 5. A linear dependence between the decay time with the displacement was also attained (see Fig. 6) although with an observable flyback effect [20]. The linear fit provided a displacement sensitivity of $11.8 \pm 0.5\ \mu\text{s}/\text{mm}$. The decay time here measured was compatible with what one would expect for a usual fiber-based CRD setup with a large 800-m ring. For comparison

purposes, Table 1 lists some decay time for other configurations.

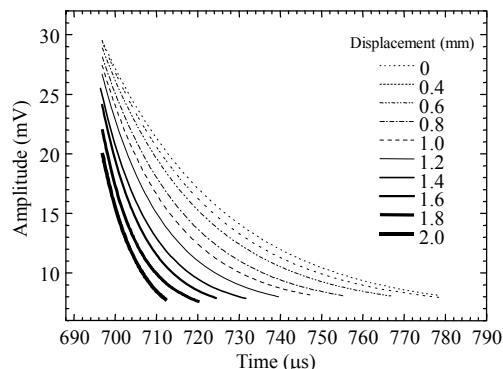


Fig. 5 Exponential fitting curves of the decaying pulse for different introduced losses (through the bending of the taper).

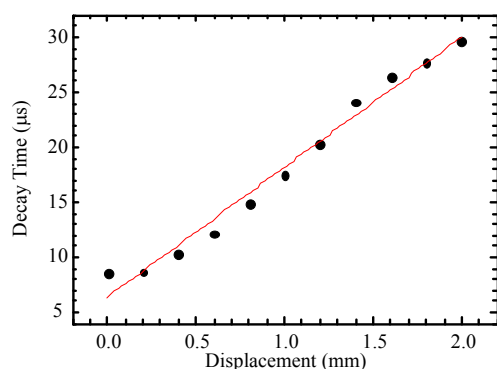


Fig. 6 Decay time taken from previous exponential fits [a greater displacement here corresponds to an extended taper (state of lower loss)].

Table 1 Round trip time and decay time for different configurations.

Articles	Ref.	Δt	τ
Fiber-loop ring-down spectroscopy	[8]	58 ns	600 ns
Fiber ring-down pressure sensors	[9]	298 ns	3.95 μ s
Fiber cavity ring-down refractive index sensor	[10]	4.3 μ s	27 μ s
Chemical sensing using fiber cavity ring-down spectroscopy	[12]	96 ns	10 μ s
Cavity ring-down for remote sensing	This work	3.9 μ s	32 μ s

4. Conclusions

This work has shown that an OTDR can be used to provide the optical pulses along an optical fiber, where multiple CRDs could potentially be placed. The setup was demonstrated with a taper sensor, placed inside the loop cavity, where the bending of the fiber taper was applied, introducing losses that were converted into a change in the decay time. This arrangement showed a sensitivity of $11.8 \pm 0.5 \mu\text{s/mm}$. The cavity ring-down technique is seen to hold some

potential through its implementation on optical fibers and also with the addition of the OTDR as a substitute of the usual laser and modulator setup. Also, the use of the OTDR as a modulation system allows reading several fiber CRD configurations in series, performing a signal processing with low losses after pulse signal optimization.

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